Evidence for three North Sea tsunamis at the Shetland Islands between 8000 and 1500 years ago

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Abstract

Coastal fen- and lake deposits enclose sand layers that record at least three Holocene tsunamis at the Shetland Islands. The oldest is the well-known Storegga tsunami (ca 8100 cal yr BP), which at the Shetlands invaded coastal lakes and ran up peaty hillsides where it deposited sand layers up to 9.2 m above present high tide level. Because sea level at ca 8100 cal yr BP was at least 10–15 m *below* present day sea level, the runup exceeded 20 m. In two lakes, we also found deposits from a younger tsunami dated to ca 5500 cal yr BP. The sediment facies are similar to those of the Storegga tsunami—rip-up clasts, sand layers, re-deposited material and marine diatoms. Runup was probably more than 10 m. Yet another sand layer in peat outcrops dates to ca 1500 cal yr BP. This sand layer thins and fines inland and was found at two sites 40 km apart and traced to ca 5–6 m above present high tide. The oldest tsunami was generated by the Storegga slide on the Norwegian continental slope. We do not know what triggered the two younger events.

1. Introduction

About 8100 calendar years ago (ca 7300 ^{14}C yr BP) a large tsunami inundated the shores around the Norwegian Sea and North Sea. The tsunami was generated from the Storegga slide (2400 km^3) west of Norway (Fig. 1; Bondevik et al., in press). Tsunami deposits from this event have been discovered in eastern Scotland (Dawson et al., 1988; Long et al., 1989; Dawson and Smith, 2000), in western Norway (Bondevik et al., 1997a; Bondevik, 2003) and the Faeroe Islands (Grauert et al., 2001; Bondevik et al., 2005). In Shetland, between Norway and Scotland (Fig. 1), a sand layer in peat had been interpreted to be deposited from a tsunami (Smith, p. 58 in Birnie et al., 1993). Radiocarbon dates of peat next to this sand layer indicated that it was deposited around 5500^{14}C yr BP, and so it appeared to be almost 2000 years younger than the Storegga tsunami. We investigated this layer more carefully and re-dated the sand layer by ^{14}C AMS dating plant fragments and wood extracted from the peat. The results showed that the sand layer represented the Storegga tsunami event and that the previous peat dates were wrong (Bondevik et al., 2003). However, during this work we discovered two younger events that we also believe represent tsunamis. These two younger events are the main focus of this paper.

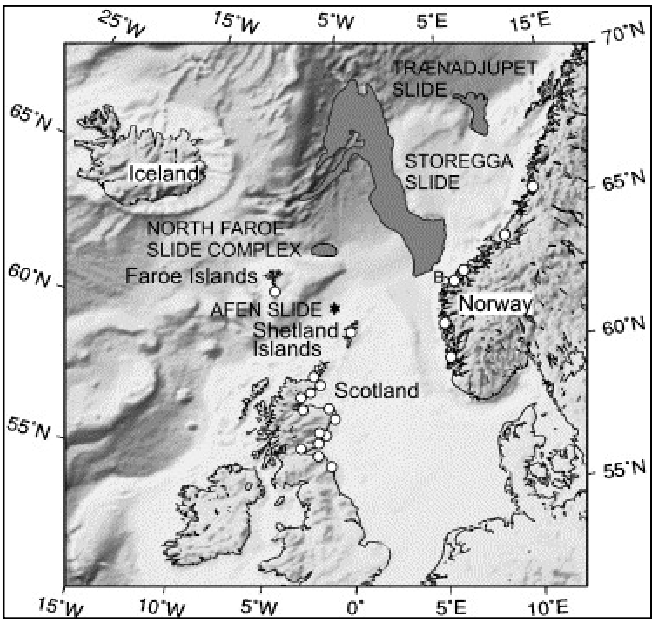


Fig. 1. Holocene slides and slide areas between Iceland, Scotland and Norway. The Storegga slide generated a major tsunami. White dots show where tsunami deposits from this event have been mapped; western Norway (runup 10–12 m; Bondevik et al., 1997a), the Faroe Islands (>14 m; Grauert et al., 2001; Bondevik et al., in press), the Shetland Islands (>20 m; this study; Bondevik et al., 2003) and NE Scotland (3–6 m; Dawson, 1999; Dawson and Smith, 2000). Other slides are the Trænadjupet slide dated to ca 4000 ^{14}C yr BP (Laberg and Vorren, 2000), the Andøya slide north of Trænadjupet (Laberg et al., 2000; not shown here) slides on the NE Faroe margin (van Weering et al., 1998) and the small Afen slide in the Faroe–Shetland Channel (Long et al., 2003). Opposite to the Afen slide on the Faroe slope of the Faroe–Shetland Channel there is also some evidence of mass flow activity at the Pleistocene/Holocene boundary (Kuijpers et al., 2001). It is not known if any of these besides the Storegga slide generated

tsunamis. The letter B in western Norway is Bergsøy.

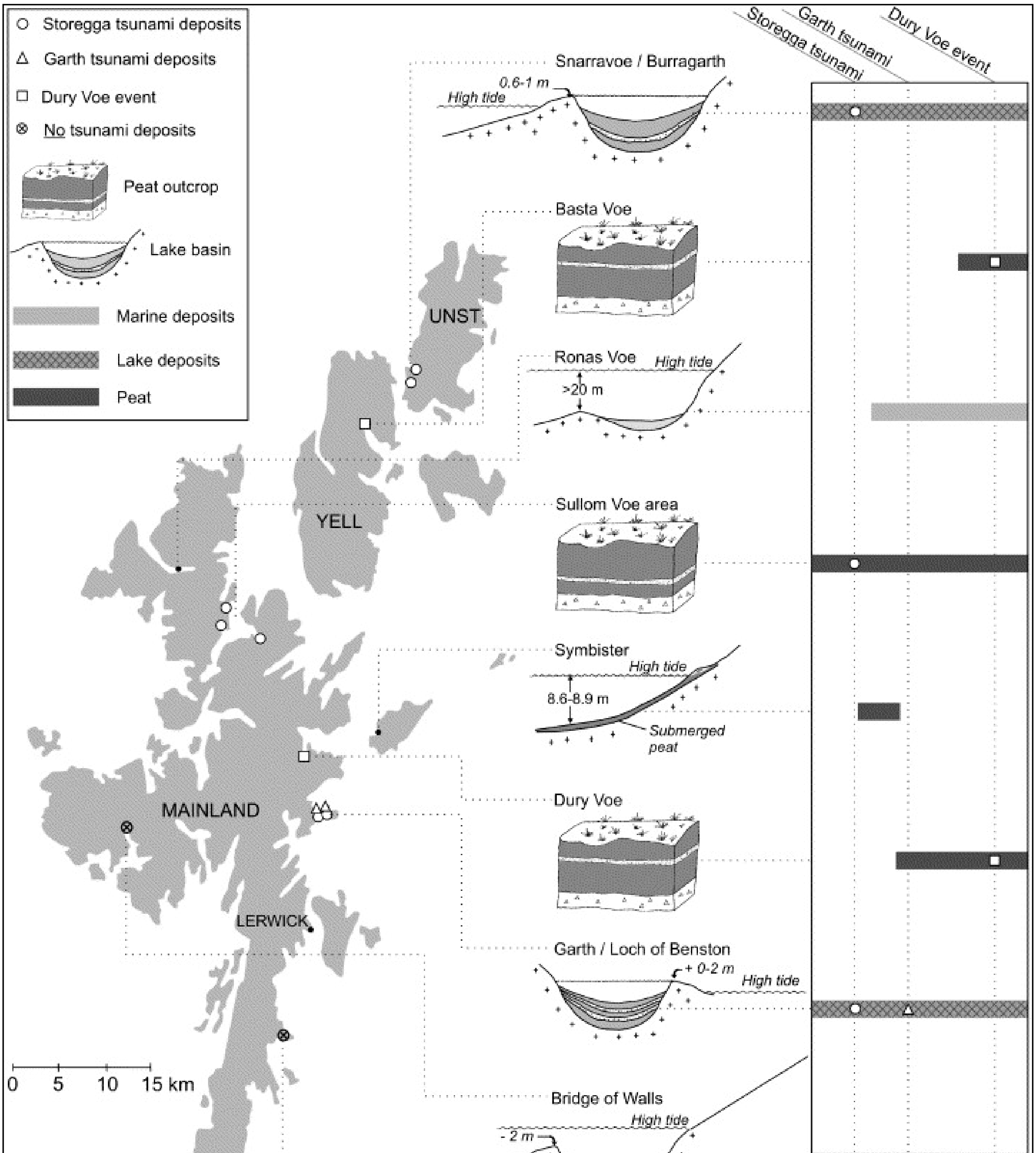
The volume, velocity and initial acceleration to a submarine slide are the important properties to whether a tsunami will be initiated from it or not. Numerical simulations indicate that slides as small as 5 km^3 in the Storegga area (Fig. 1) could generate waves with surface elevations of about 1–3 m along the Norwegian coast (De Blasio et al., 2003; Løvholt et al., 2005). Mapping of the sea floor in the recent years has revealed other large Holocene slides (Fig. 1) as the Trænadjupet slide (Laberg and Vorren, 2000); the Andøya slide (Laberg et al., 2000), a slide area on the NE Faroe margin (van Weering et al., 1998; Kuijpers et al., 2001) and the small Afen slide (Long et al., 2003). Except for the Afen slide all of these slides are probably large enough to generate tsunamis.

In this paper, we report deposits from three separate tsunamis on Shetland. The oldest is the Storegga tsunami; deposits from which are present both in peat outcrops and lakes (Bondevik et al., 2003). Two lake basins also contain a younger event dated to ca 5500 cal yr BP which sediment facies are similar to the Storegga tsunami. The youngest event dates to ca 1500 cal yr BP and is a thin sand layer in peat.

2. Depositories for tsunami sediments and methods

Tsunami deposits are well preserved in coastal lakes inundated by tsunamis (e.g. Bondevik et al., 1997b). Shetland has about 2500 freshwater lakes, called lochs. Some are cut off from the sea by beach bars, many have been formed behind barriers of peat blocking the drainage of flat areas, but at least 1000 occupy rock basins carved out by glacier ice (Flinn, 1980). In this study, we have cored several such lake basins with a bedrock threshold close to present sea level.

Peat offers another possible depository for tsunami sediments. The modern land surface on Shetland is to a large extent covered by actively growing blanket peat. Blanket peat is typically found on slopes less than 15° in areas of high rainfall (Birks and Birks, 1980). The annual rainfall on Shetland, Lerwick (Fig. 2) is 1029 mm (Irvine, 1968), and together with the gentle slopes, many places are favourable for the growth of peat. We searched the extensive peat outcrops along the shores for tsunami deposits and also cored some low-lying bogs.



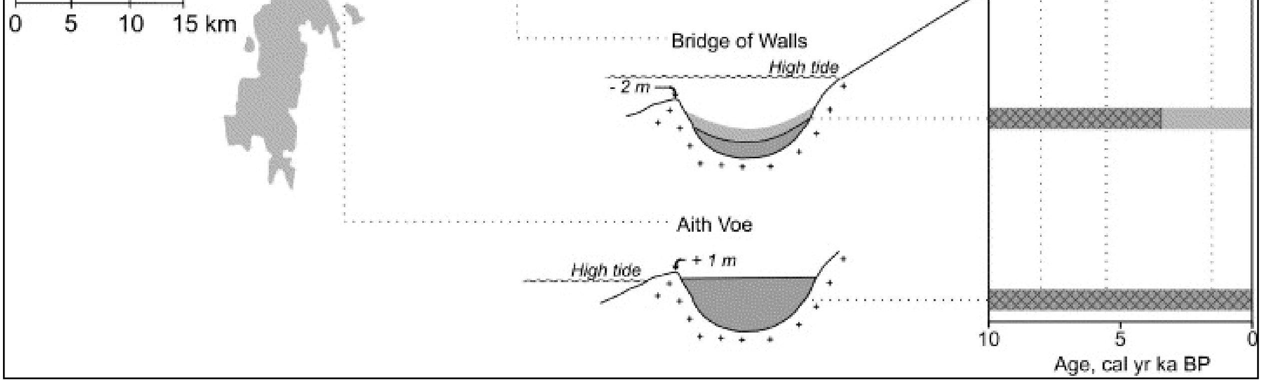


Fig. 2. The sites on Shetland discussed in this paper. All ages in calibrated years before present.

Fieldwork was undertaken during the last 2 weeks of August in 2001 and 2002. Sand layers in peat were described, sampled, levelled from high tide and traced to their highest elevation. Samples of peat were cut out from the outcrops, wrapped tightly in plastic foil and brought back to the laboratory for further analysis. We also pushed and hammered 110 mm PVC tubes vertically into the peat to extract the deposits. To core the lake- and marine basins we used “Russian” peat cores (60–100 mm in diameter) and a 110 mm piston corer. In open water, a raft anchored to the shore was used as coring platform.

Cores and peat blocks were studied in the laboratory. Some sand layers were X-radio graphed for the study of sedimentary structures. Grain size data were obtained from wet sieving the sand. The samples were heated to 550 °C to burn off organics before sieving. To measure loss on ignition, the samples were dried at 105 °C for 24 h and then heated to 550 °C for 2 h. Weight loss was calculated as a percentage of the dried sample weight.

Samples of peat and lake mud for radiocarbon dating were cut from the cores or peat blocks. After soaking in water, the peat or lake mud was sieved with water at 250 •m. The materials >250 •m were then studied under a stereo-microscope and fragments suitable for ^{14}C AMS dating were picked out and identified. The fragments were cleaned and dried in 40 °C and submitted to the Trondheim radiocarbon laboratory where targets were produced. AMS measurements of these targets were performed at the Svedberg laboratory at the University in Uppsala, Sweden. Some larger samples were dated with the conventional method at the radiocarbon laboratory in Trondheim. ^{14}C ages were calibrated to calendar years at 2σ using Calib ver. 4.2.2 (Stuiver and Reimer, 1993) (Table 1).

Table 1.

Radiocarbon dates

Laboratory number	Core/ sample	Location	Context	Material dated	^{14}C age (yr BP)	$\delta^{13}C$ (‰ PDB)	Cal yr BP 2σ	Rel. area u. prob. distr.
TUa-3432	Sh-03-01	Bridge of Walls	Marine gyttja at 241 cm in core.	Small gastropods: 8 *Hydrobia ulvae* (12.6 mg).	840±55	0.8	330–550	1.000
TUa-4917	Sh-03-01	Bridge of Walls	Brackish gyttja at 279–281 cm in core.	Plant fragments: About 30 seeds of *Ruppia* sp. (10 mg), frags. of insects, bark, leaves and moss stems (total 15.0 mg).	3520±50	−17.7	3465–3705[a]	0.993
TUa-3492	Sh-03-01	Bridge of Walls	Lacustrine gyttja, just below brackish gyttja at 281–283 cm in core.	Plant fragments: 2 flowers, frags. of bark, twigs and leaves, moss stems and seeds (11.5 mg).	3340±55	−28.9	3450–3700	0.999
T-15635	Sh-05-03	Ronas Voe	Lowest shell in core Sh-05-03, sample no. Sh 01/26.	Shell: Paired *Mya truncata* (6.9 g).	6810±95	1.6	7150–7510	1.000
T-15633	Sh 01/21	Maggie Kettle's Loch	Tree root embedded in sand layer.	Wood: Many tiny roots within cracks in the wood were carefully removed (8.95 g).	7905±40	−28.7	8600–8790	0.689

T-15634	Sh 01/22c	Maggie Kettle's Loch	Tree root embedded in sand layer.	Wood: Many tiny roots within cracks in the wood and between the wood and the bark were carefully removed (12.79 g).	6985±50	–29.1	7690–7870	0.860
T-16021	Sh 01/06	Maggie Kettle's Loch	Stick (5×8) cm, with bark in sand layer.	Wood: Dense wood, tiny roots between the wood and the bark were carefully removed (50.46 g).	7375±65	–30.2	8110–8340	0.792
T-16020	Sh 01/57	The Houb	1–3 cm above the upper boundary of the sand layer.	Wood: Stick, 10 cm long, possibly *Betula*, probably from a root (10.2 g).	7025±60	–27.9	7720–7960	0.985
TUa-3425	Sh 01/53	The Houb	0–1 cm above the upper boundary of the sand layer.	Wood: One twig with bark, possibly *Betula*. Tiny roots underneath the bark were removed (1.0 g).	6740±70	–30.7	7460–7690	0.993
TUa-3491	Sh 01/53	The Houb	0–1 cm below the lower boundary of the sand layer.	Plant fragments: 3 twigs or roots (possibly *Calluna*) with bark, the longest 40 mm. In addition a few bark frags. (25.4 mg).	6705±60	–29.1	7460–7670	0.997
TUa-3903	Sh-10-02	The Houb	0–1 cm below the lower boundary of the sand layer.	Plant fragments: More than 40 seeds and some *Coleoptera*-fragments (10.7 mg).	7120±60	–25.7	7820–8030	0.946
TUa-3904	Sh-10-02	The Houb	15–16 cm below the lower boundary of the sand layer.	Plant fragments: More than 30 seeds and some *Coleoptera*-fragments (9.2 mg).	7985±60	–26.1	8640–9010	1.000
TUa-3905	Sh-10-02	The Houb	35–37 cm below the lower boundary of the sand layer.	Plant fragments: More than 50 seeds (14.5 mg).	9245±75	–27.7[b]	10240–10580	0.986
TUa-3431	Sh-07-02	Garth Loch	Just above the upper tsunami layer at 207 cm in core.	Plant fragments: Small twigs (11.0 mg).	4645±65	–27.8	5280–5490	0.803
TUa-3430	Sh-07-01B	Garth Loch	Just below the upper tsunami deposit at 220–222 cm in core.	Plant fragments: A few leaf fragments, twigs (15.9 mg).	4895±70	–29.4	5570–5750	0.830
TUa-3429	Sh-07-01B	Garth Loch	In homogeneous gyttja between the two tsunami facies at 260–262 cm in core.	Plant fragments: Leaves of *Betula pubescens*, and *Salix* sp. (willow) and *Ledum palustre?* Catkin scales and seeds (with wings) probably from *B. pubescens* (24.0 mg).	6450±75	–29.4	7250–7490	0.985

TUa-3428	Sh-07-01B	Garth Loch	Gyttja, just above the lower tsunami deposit at 298–300 cm in core.	Plant fragments: Leaves of *Betula pubescens*, and possibly *Salix* sp. (willow) and *Ledum palustre?* Catkin scales and seeds (with wings) probably from *B. pubescens* (11.1 mg).	7220±70	–27.9	7930–8170	0.967
TUa-3427	Sh-07-01D	Garth Loch	From within the tsunami deposit at 390 cm in core.	Wood: 6 cm long *Salix* sp. twig (0.47 g).	7320±70	–25.5	7970–8210	0.910
TUa-3909	Sh-09-01B	Loch of Benston	From within the upper tsunami deposit at 362 cm in core	Plant fragments: 4 cm long twig with bark, probably *Betula pubescens* (0.16 g).	4965±55	–29.6	5590–5760	0.841
TUa-3487	Sh 01/33	Dury Voe	1–2 cm above upper boundary of the sand layer.	Plant fragments: 9 seeds, 2 catkin scales, 1 frags. of charcoal and bark >1 mm+many small frags. (0.5–1 mm) of charcoal, twigs and insects (14.7 mg).	1460±50	–28.1	1290–1420	0.939
TUa-3488	Sh 01/33	Dury Voe	1–2 cm below the lower boundary of the sand layer.	Plant fragments: 10 charcoal frags., 4 frags. of insects >1 mm. In addition many small frags. (0.5–1 mm) of charcoal, twigs and insects (25.6 mg).	1745±60	–28.8	1540–1820	1.000
TUa-3489	Sh 01/33	Dury Voe	7–8 cm below the lower boundary of the sand layer.	Plant fragments: 7 small charcoal fragments, 4 fragments of insects. Small twigs and bark fragments (10.5 mg).	2105±55	–29.7	1950–2160	0.864
T-16544	Sh 01/32	Dury Voe	62 cm below the lower boundary of the sand layer.	Wood: Stick, 12.5 cm long, piece from a root (6.05 g).	4910±90	–27.0	5570–5890	0.870
TUa-3495	Sh-08-01	Basta Voe	At 41.5 cm depth in core; 25 cm above upper boundary of uppermost sand layer.	Plant fragments: Twig with bark, 5 mm×20 mm, possibly *Calluna*. A few tiny roots underneath the bark were removed (39.8 mg).	1170±50	–27.6	970–1180	0.963
TUa-3496	Sh-08-01	Basta Voe	At 61 cm depth in core; 5 cm above the upper boundary of uppermost sand layer.	Plant fragments: 3 twigs (possibly *Calluna*) with bark. (a) 10 mm×2 mm with bark, (b) 5 mm×3 mm with bark and (c) 1 mm×2 mm. Tiny roots removed (18.0 mg).	1505±60	–27.8	1300–1520	1.000
TUa-3490	Sh 01/45	Basta Voe	0–1 cm below the lower boundary of uppermost sand layer.	Plant fragments: 3 twigs (possibly *Calluna* sp.) with bark. (a) 2 mm×15 mm, (b) 1.5 mm×12 mm and (c) 2 mm×20 mm. Tiny roots removed (22.9 mg).	1570±55	–28.6	1330–1570	1.000

TUa-3497	Sh-08-01	Basta Voe	At 94–95.5 cm depth in core; just below second sand layer.	Plant fragments: 2 twigs (possibly *Calluna* sp.) with bark. (a) 2 mm×4 mm, (b) 1 mm×7 mm and (c) seeds. In addition a few smaller twigs (12.0 mg).	2060±60	−28.2	1880–2150	0.980
TUa-3498	Sh-08-01	Basta Voe	At 122 cm depth in core.	Plant fragments: Twig with bark (root?) 30 mm×8 mm. Tiny roots removed (0.32 g).	2435±65	−28.9	2350–2710	1.000
TUa-3499	Sh-08-01	Basta Voe	At 140–141 cm in core; just below the third sand layer.	Plant fragments: Twigs with bark. All have tiny roots underneath the bark. These were carefully removed (19.0 mg).	2880±65	−29.0	2850–3210	0.996
TUa-4918	Sh-11-02B	Loch of Snarravoe	18.5–20 cm above upper boundary of tsunami layer.	Plant fragments: Most material is moss stems (*Eurhynchium* sp.), a few frags. of charcoal and 1 leaf frags. (28.0 mg).	7065±55	−36.8	7790–7970	0.956

Note: All ^{14}C ages were calibrated to calendar years using Calib ver. 4.2.2 Stuiver and Reimer (1993) based on the calibration data in Intcal 98 Stuiver et al. (1998). Marine samples were calibrated using a ΔR value of −5±27 (regional mean for the North Sea; in marine reservoir correction database: http://radiocarbon.pa.qub.ac.uk/marine). Calibrated ages are rounded to the nearest 10 yr. Weights refer to dry weights of samples when submitted to radiocarbon laboratory.
[a] Sample assumed to be a mixture of marine and terrestrial carbon (50% marine carbon).
[b] Assumed value, not measured.

Diatoms were analysed from selected levels to confirm marine provenance of the samples (Table 2). A minimum of 300 valves per level were identified using mainly Van der Werff and Huls (1958–66) and Hendey (1964). Diatom nomenclature follows Hartley (1986) and salinity and life form classification is based on Denys (1991/2) and Vos and de Wolf (1993).

Table 2.

Diatom analysis, Garth Loch

Core	**Depth (cm)**	**Context**	**Marine/brackish species (dominating)**	**Freshwater species (widely occurring)**	**Marine/brackish species (%)**
Sh-07-01-D	398	Storegga tsunami: In coarse sand, 2 cm above lower boundary.	*Paralia sulcata*, *Navicula peregrina*, *Mastagloia smithii*, *Achnanthes delicatula*, *Diploneis interrupta*.	*Epithemia sorex*, *Fragilaria construens*, *Fragilaria construens var venter*, *Fragilaria pinnata*, *Cocconeis placentula*.	31.4
Sh-07-01-B	218.5	Garth tsunami: In medium sand at the lower boundary.	*Paralia sulcata*, *Navicula peregrina*, *Mastagloia smithii*.	*Epithemia sorex*, *Fragilaria construens*, *Fragilaria construens var venter*, *Fragilaria pinnata*, *Cocconeis placentula* and *Navicula pusilla*.	41.1
Sh-07-01-B	215.5	Garth tsunami: In medium sand, 3 cm above the lower boundary.	*Paralia sulcata*, *Navicula peregrina*, *Mastagloia smithii*.	*Epithemia sorex*, *Fragilaria construens*, *Fragilaria construens var venter*, *Fragilaria pinnata* and *Cocconeis placentula*.	46.9
Sh-07-02	214	Garth tsunami: In medium to fine sand at the lower boundary.	*Paralia sulcata*, *Navicula peregrina*, *Mastagloia smithii*.	*Epithemia sorex*, *Fragilaria construens*, *Fragilaria construens var venter*, *Fragilaria pinnata* and *Cocconeis placentula*.	44.5

Sh-07-02	209	Garth tsunami: In fine sand at the upper boundary.	*Paralia sulcata*, *Navicula peregrina*, *Mastagloia smithii.*	*Epithemia sorex*, *Fragilaria construens*, *Fragilaria construens var venter*, *Fragilaria pinnata* and *Cocconeis placentula*.	48.2

3. Sea level changes on Shetland

In order to estimate tsunami runups, the sea level at the time of the tsunamis has to be known. On Shetland, marine sediments or other landforms associated with shore processes do not exist onshore. Around the entire islands, present beach ridges can be found to rest on peat. For instance at Maggie Kettle's Loch (Fig. 5) we found about a metre of peat beneath the present beach ridge.

The Holocene sea level history on Shetland has never been investigated in any detail and only a few data exist. An in situ peat was found between 8.6 and 8.9 m below high tide level at Symbister harbour (Fig. 2) and dated to between 5990 and 7900 cal yr BP (Hoppe, 1965). These dates indicate that sea level at ca 6000–7000 cal yr BP was at least 9 m below present sea level. We also collected data on the sea level history as described below.

3.1. The loch just inside of the Bridge of Walls

At the Bridge of Walls, to the west on the Mainland (Fig. 2), there is a shallow marine basin at the very head of the Voe (Fig. 3). The threshold of the basin is ca 2 m below high tide level, and presently brownish-black marine gyttja (organic mud) is deposited in the basin. Loss on ignition is high, just above 30% (Fig. 3). A large number of small gastropods (*Hydrobia ulvae*) are present in the marine mud. The deposits were inspected with a Russian peat corer and a 170 cm long piston core was collected. The core has lacustrine gyttja in the lower part and black marine gyttja with small gastropods in the upper part.

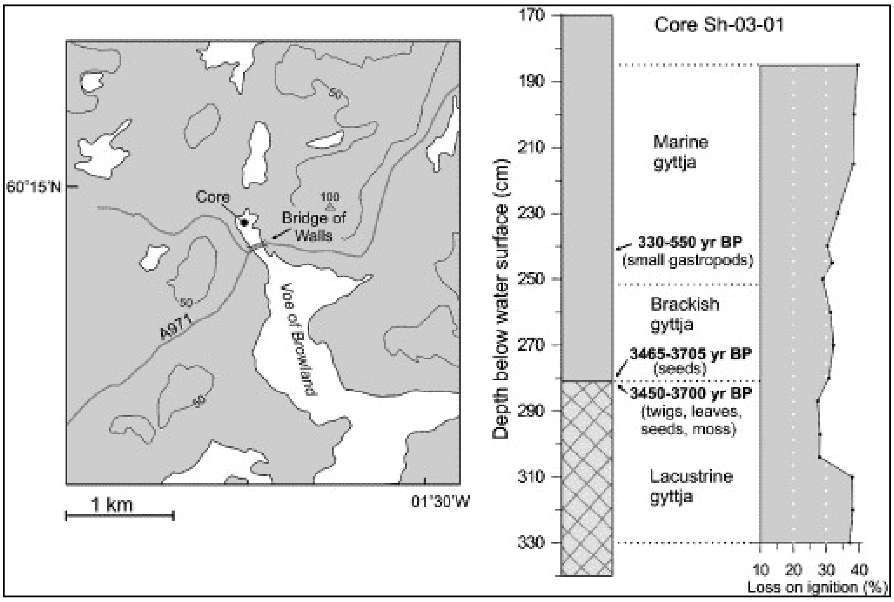


Fig. 3. A shallow marine basin is located just north east of the Bridge of Walls. The bedrock threshold, just to the south of the bridge, is ca 2 m below high tide. Presently black marine gyttja accumulates in the basin. A core collected at 60°14.778′N and 1°31.961′W (site on map) has brown lacustrine gyttja in the lower part and black marine gyttja in the upper part. Brackish water entered the basin for the first time after 3450–3700 yr BP (3340±55 ^{14}C yr BP; Table 1).

A few levels in the core were checked for diatoms and they show fresh water species between 340 and 283 cm, brackish between 283 and 251 cm, and from 251 cm and upwards the diatoms indicate a marine environment (Fig. 3). From 241 cm and upwards gastropods *H. ulvae* are present. The loss on ignition curve (Fig. 3) does not show changes linked to the different environments in the basin. We obtained two ^{14}C dates from the core (Table 1) at the boundary between lacustrine- (at 283–281 cm: 3450–3700 cal yr BP) and brackish-water gyttja (at 281–279 cm: 3465–3705 cal yr BP). These dates show that the high tides reached 2 m lower than today at 3450–3700 cal yr BP.

3.2. Ronas Voe

The fjord Ronas Voe, northwest on the Mainland (Fig. 2) has a shallow sill at the entrance. According to bathymetric maps (1: 75,000) the greatest depth across the sill is between 14 and 20 m. At the time when sea level was below the sill, Ronas Voe must have been a large freshwater lake. We cored three sites in the inner part of the fjord at ca 60°30.631′N and 1°24.780′E (Fig. 2) hoping to penetrate the marine deposits into lake deposits. The plan was to ^{14}C date the transition from lacustrine to marine environment in this basin. However, we did not succeed, and the 3–4 m long cores held only marine sediments. The lowermost shell was dated to 7150–7520 cal yr BP (Table 1), giving a minimum age for the connection of the basin to the sea.

3.3. Preliminary sea level curve for Shetland

The ^{14}C dates of the submerged peat at Symbister (Fig. 2 and Fig. 4) show that sea level was lower than 8.9 m below high tide when the peat accumulated some 6000–7000 yr BP (Hoppe, 1965). The transgressed lake at Bridge of Walls indicate further that the high tide sea level was 2 m lower at about 3500 cal yr BP (Fig. 3 and Fig. 4). The sea level curve modelled by both Lambeck (1993) and Peltier et al. (2002) predicts sea level to be 1–3 m lower than our dates indicate for the last 5000 cal yr (Fig. 4).

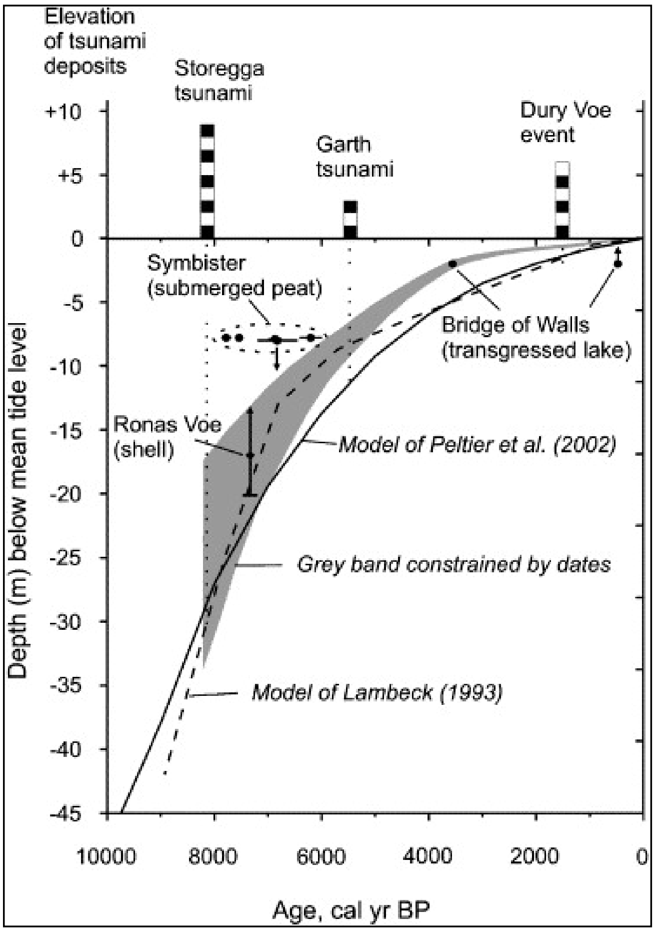


Fig. 4. A preliminary sea level curve for Shetland shown as a grey band constrained by ^{14}C dates. The ^{14}C dates are from the basin at Bridge of Walls (2 m below high tide), in situ peat (8.9 m below high tide) at Symbister (Hoppe, 1965) and a shell date from Ronas Voe (Fig. 2). Both the modelled sea level curves of Lambeck (1993, stippled line) and Peltier et al., (2002, solid line) predict sea levels that are 2–3 m lower than our dates indicate for the last 4000 cal yr. Sea levels when the different tsunamis happened are indicated together with runup of the deposits above present day high tide level. All ^{14}C ages in calibrated years.

When the Storegga tsunami happened at about 8100 cal yr BP relative sea level was clearly lower than 10 m below present day high tide. Both modelled sea level curves (Lambeck, 1993; Peltier et al., 2002) show the sea level at that time to be as low as about 30 m lower than now. According to the extrapolated sea level curve constrained by ^{14}C dates (Fig. 4) sea level was somewhere between −15 and −30 m when the Storegga slide occurred.

4. The Storegga tsunami event at the Shetland Islands

4.1. A sand layer in peat

At both sides of the Sullom Voe (Fig. 2) there is a distinct sand layer in peat. At Garths Voe (Fig. 5) the sand layer, first discovered by Birnie (1981), was traced up to ca 6 m above high tide and interpreted to be a tsunami deposit by Smith (p. 58 in Birnie et al., 1993). Radiocarbon dates of 1-cm slices of bulk peat at contacts above and below the layer were dated by them to 5700 ^{14}C yr BP below and 5300 ^{14}C yr BP above the sand layer, almost 2000 years younger than the age of the Storegga tsunami. As mentioned above, this sand layer was what attracted us to Shetland in the first place. It is now re-dated to represent the Storegga tsunami (Bondevik et al., 2003).

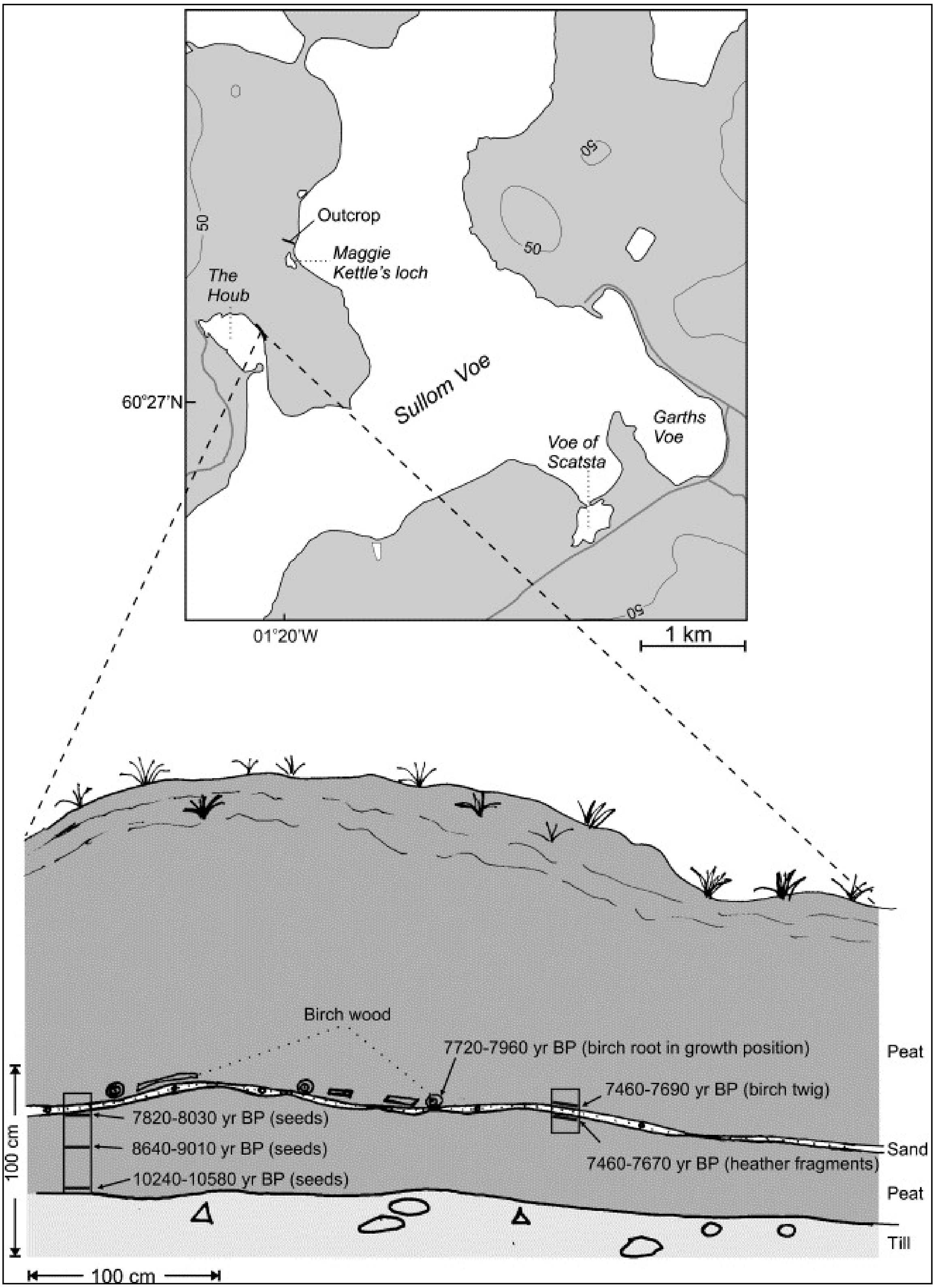


Fig. 5. A 4-m long section of the outcrop along the north-eastern shore of the Houb. The sand layer extends for 150 m along the outcrop, is 1–5 cm thick and is found at ca 40 cm above the boundary to the till. Just above the sand there is a horizon in the peat of many remains of birch trees, mainly birch roots in growth position. A radiocarbon date from here shows that the sand layer is older than 7720–7960 cal yr BP (7025±60 ^{14}C yr BP). Other dates are AMS dates on seeds or plant fragments extracted from the peat. The date of 7460–7670 cal yr BP (6705±60 ^{14}C yr BP) below the sand was measured on *Calluna* sp., identified as either twigs or roots. This young age indicates that it probably was a root penetrating below the sand layer. See Table 1 for further information about dated samples. Boxes show sample/core.

We searched for possible tsunami layers around the entire Sullom Voe and found sand beds we interpreted as tsunami layers on the east shores of Sullom Voe (Fig. 2). However, much larger sections, and more interesting deposits, were found at two sites on the western side of Sullom Voe, called Maggie Kettle's Loch and The Houb (Fig. 5). The outcrop at Maggie Kettle's Loch shows extensive evidence of erosion of the peat and many rip-up clasts of peat are scattered in the tsunami sand. Details of this site were recently published (Bondevik et al., 2003).

Along the northern and eastern shore of the Houb the sea has recently eroded into peat and till exposing a 1–3 m high outcrop (Fig. 5). In the lower part of the peat, there is a 1–5 cm thick, wide-spread sand layer, resting on 30–40 cm of peat (Fig. 5). The sand layer is more or less continuous for more than 150 m along the outcrop. The grain size is medium to coarse sand, occasionally containing a few gravel particles. The layer is interpreted to be deposited by the same tsunami as described from Maggie Kettle's Loch to the north (Fig. 5; Bondevik et al., 2003) and the sand layers on the east side of Sullom

Voe (Fig. 2). Just above the sand there is a horizon in the peat containing remains of birch trees. From here part of a root in growth position was ^{14}C dated to 7720–7960 cal yr BP (7025±60 ^{14}C yr BP). Extracted seeds from the peat immediately below the sand layer (Fig. 5, Table 1) were dated to 7820–8030 cal yr BP (7120±60 ^{14}C yr BP). Based on these dates (Fig. 5) we conclude that the sand layer was deposited from the Storegga tsunami.

These new dates indicate that the previous bulk dates of peat above and below the sand layer (Birnie et al., 1993) were 1500–2000 years too young. Radiocarbon dating of peat is well known to be problematic (e.g. Shore et al., 1995). The main problem arise from the deep penetration of roots (Nilsson et al., 2001) that transfer current atmospheric CO_2-carbon to deeper layers, thus reducing the ^{14}C age of the affected peat. Another problem can arise due to the redistribution of dissolved organic matter, for example by humic acids transported by ground water. AMS dates on individual plant fragments extracted from the peat minimize the problem of obtaining false ages.

4.2. Storegga tsunami deposits in lake basins

Deposits consisting of typical tsunami facies (Bondevik et al., 1997b) and of Storegga tsunami age were discovered in four near-shore lakes in the north-eastern part of Shetland (Fig. 2). Two lake basins on the south-western side of the island of Unst show only one tsunami event—the Storegga tsunami (Fig. 6). Two other basins, farther south on the eastern coast of the Mainland (Fig. 2), show Storegga tsunami deposits overlain by lake sediments and the Garth tsunami (ca 5500 cal yr BP) event (Fig. 7).

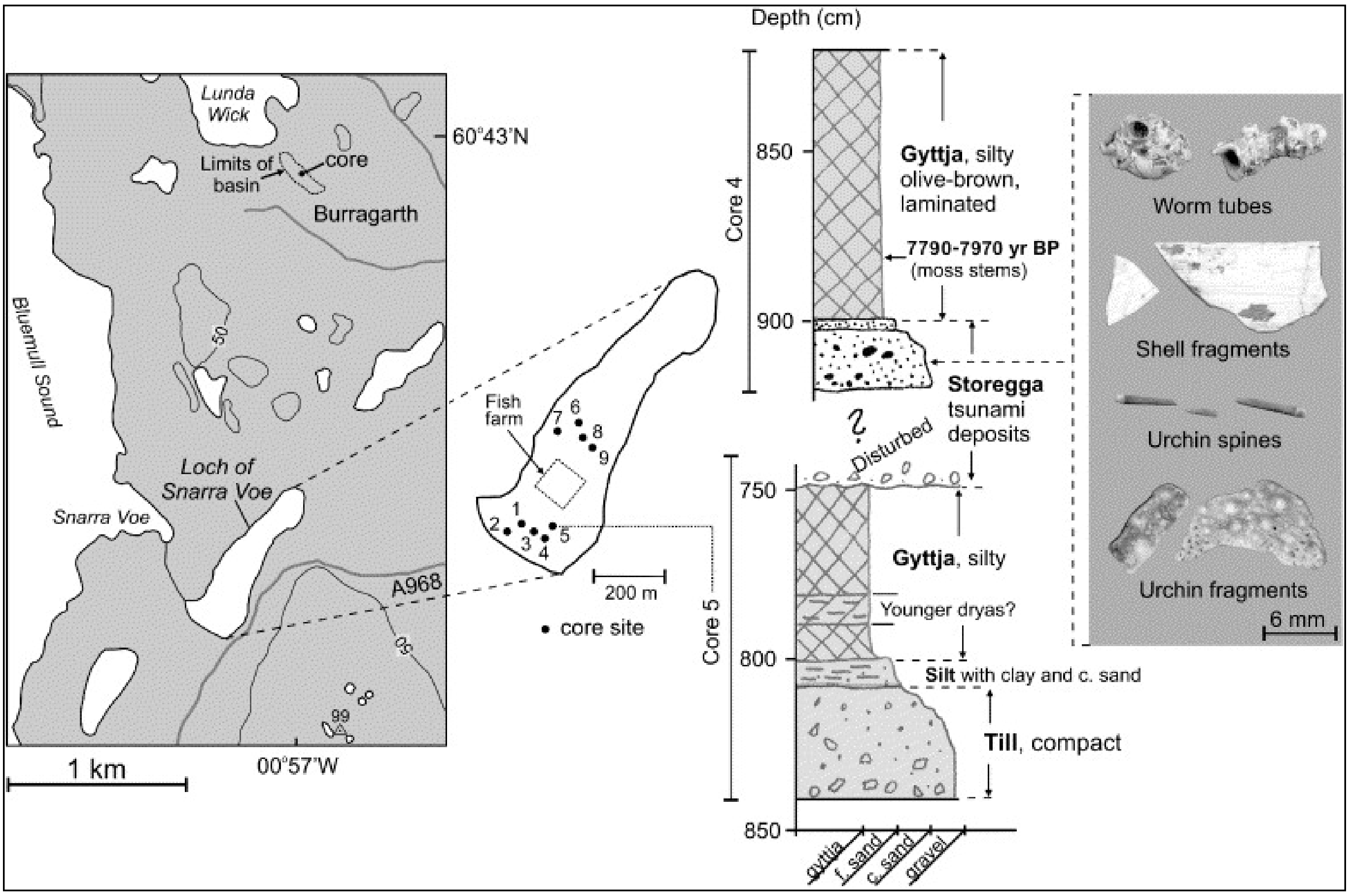


Fig. 6. Loch of Snarravoe is located 0.6 m above high tide (Fig. 2). Nine locations were cored using a Russian peat corer and at core site 5 we used the 110 mm corer, and here were able to penetrate through the tsunami deposits and into compact till. Only one tsunami layer is present in the stratigraphy —the Storegga tsunami. The tsunami deposits consist of sand and gravel having many rounded clasts of over-consolidated silt indicating considerable erosion and transport by the tsunami wave. Also the tsunami sand contains different marine shell fragments, as shown on the photograph to the right. At core site 6–9 as much as 6 m of organic laminated gyttja lies on top of the tsunami deposits. A radiocarbon date from core site 9 at 18.5–20 cm above the upper boundary of the tsunami deposits (Table 1) yielded 7785–7974 cal yr BP (7065±55 ^{14}C yr BP). The basin north of Loch of Snarravoe, called Burragarth, also shows only one tsunami event—the Storegga tsunami (core not presented here; see also Smith in Birnie et al., 1993).

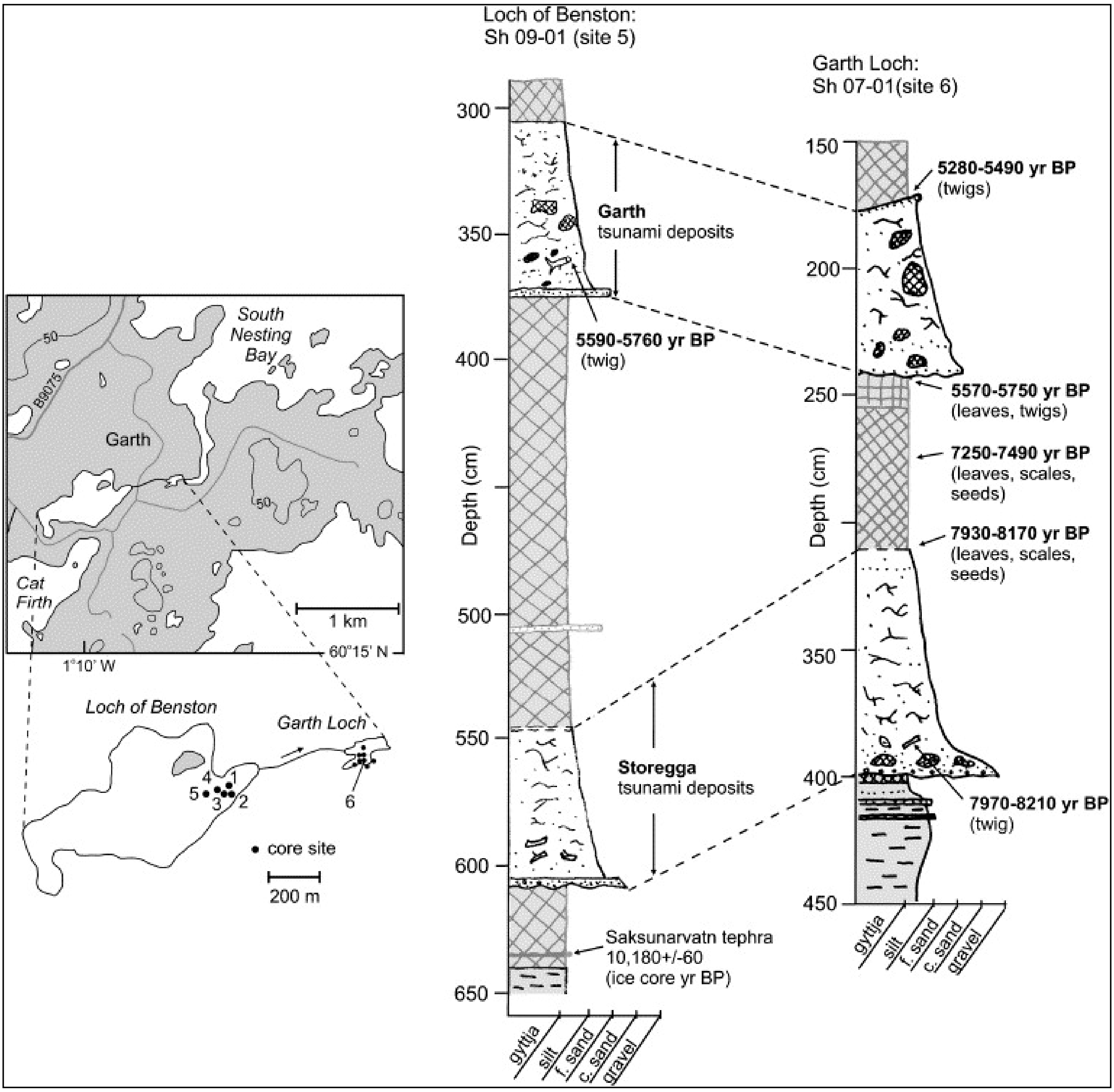


Fig. 7. Loch of Benston and a smaller lake basin we have called Garth Loch, is located in Garth in South Nesting (Fig. 2). Garth Loch is just above the high tide level, while Loch of Benston is found 1.6 m higher and drains into Garth Loch. Both basins show tsunami deposits dated to between 5300 and 5700 cal yr BP—in superposition to the Storegga tsunami deposits. Diatoms were analysed from selected levels within the sand of each tsunami deposit and show that about 45% of the diatoms are marine species (Table 2). See Table 1 for details about the ^{14}C-dated samples and calibrated ages.

4.3. Runup of the Storegga tsunami on Shetland

The sand bed in peat at Maggie Kettle's Loch was traced to 9.2 m above high tide. We also traced it in hand cores to continue 2.4 m below high tide in peat underneath the present day beach gravel. Thus, we have measured a minimum runup of 11.6 m (Bondevik et al., 2003). Relative sea level when the Storegga tsunami happened was at least 10–15 m below the present (Fig. 4), giving a runup of more than 20–25 m for this site. Numerical modelling of the Storegga tsunami indicates a runup of 19–21 m in a water depth of 48 m about 3 km north of Maggie Kettle's Loch in Sullom Voe (Bondevik et al., 2005).

The four lakes mentioned above are all located less than 3 m above high tide. The deposits show that the tsunami overflowed the outlet threshold of the lake, indicating a runup of minimum 3 m above the present high tide. For the lakes located on the eastern and northern coast the runup may have been less than the 20–25 m found for the Sullom Voe area, but still larger than 12–15 m.

5. The Garth tsunami event (ca 5500 cal yr BP)

In Garth in South Nesting (Fig. 2 and Fig. 7), we cored two lake basins close to present sea level. The first, named Garth Loch by us is a small lake basin found just above the high tide level. The other is Loch of Benston, draining into Garth Loch and located at 1.6 m higher elevation (Fig. 7). Both lakes show a similar stratigraphy with two superimposed units consisting of typical tsunami facies, separated by normal lacustrine deposits. The oldest is dated to Storegga tsunami age and the younger tsunami deposit dates to ca 5500 cal yr BP. The occurrence of two stratigraphically superimposed units of tsunami-type facies in two lakes at different elevations is an additional argument for both units being tsunami deposits. Here follows a presentation of the deposits in those two lakes.

5.1. Garth Loch

Garth Loch has a bedrock threshold towards the very narrow inlet from the sea (Fig. 7). The small lake basin is almost filled in with deposits and the surface consists of islands of peat with open water in between. The peat has been eroded by seawater during spring tides and storms, and it was probably a continuous cover of peat on top of the lake sediments before this erosion, which is due to the recent sea level rise. We cored 8 sites in the central area of the basin covering an area of ca 40 m×60 m. The cores revealed two distinct and separate layers of tsunami deposits. The following description is from core Sh 07-01 at core site 6, a representative core of the stratigraphy in this basin (Fig. 7).

Late glacial/early Holocene: Late glacial silt with various amounts of gyttja and sand is present in the lower part of the basin. There is a gradual change from the underlying grey silt to olive brown silty gyttja at 402 cm. This change represents probably the Late glacial/Holocene transition.

Storegga tsunami deposits: At 398.5 cm there is an erosive, sharp boundary against the underlying gyttja. On this boundary there is a 1.5 cm thick layer of very coarse sand and fine gravel particles (2–6 mm) that fines upwards to a 4 cm thick bed of coarse sand. The sand contains three distinct rip-up clasts; one of light grey silt, another of olive grey silt and the third is light brown sandy gyttja. The clasts float in the sand and are between 2 and 4 cm long (Fig. 7). Around 30% of the diatoms in the sand are marine and brackish species (Table 2). No shell fragments were found. Above the sand bed the deposit is a mixture of various plant fragments, lake mud and sand. A twig at 390 cm was dated to 7970–8210 cal yr BP (7320±70 ^{14}C yr BP, Table 1 and Fig. 7). The upper boundary at 311 cm is gradual.

Lacustrine gyttja between the two tsunami deposits: Between the two tsunami deposits there is 70 cm of gyttja. Three AMS ^{14}C dates show that it was deposited between 7930–8170 cal yr BP (7220±70 ^{14}C yr BP) and 5570–5750 cal yr BP (4895±70 ^{14}C yr BP, Table 1 and Fig. 7).

The second tsunami deposits: At 241 cm a thin lamina of medium to fine sand is found on the very sharp boundary to the underlying gyttja. Several clasts of different coloured gyttja are found within the interval 241–230 cm (Fig. 7). Many of the clasts have a rim of sand around them. Four samples of sand from this unit in two different cores were analysed and all show about 45% of marine and brackish diatoms (Table 2). From 230 cm and upwards to 174 cm the sediment is a mixture of gyttja, sand and plant material with large clasts of dark brown gyttja floating in the sediments. At 175–174 cm there is a fine sand/silt lamina, possibly graded that marks the upper boundary of the tsunami facies.

Organic deposits above the second tsunami deposits: The upper 170 cm is a brown coarse detritus gyttja that changes into peat upwards towards the surface. Two tiny twigs just above the second tsunami facies were dated to 5280–5490 cal yr BP (4645±65 ^{14}C yr BP, Table 1 and Fig. 7).

5.2. Loch of Benston

The deposits in Loch of Benston are very similar to the deposits in Garth Loch. Both lakes contain two separate units of tsunami facies which are very similar regarding thickness, the content of rip-up clasts, and sand. The difference is the amount of erosion from the tsunami events. In Garth Loch, there was only a very thin layer of gyttja between the Late glacial silt and the Storegga tsunami deposits. In Loch of Benston, we found 30 cm of gyttja and a tephra layer (Fig. 7). Microprobe analyses of ash particles (Table 3) prove the tephra layer to belong to the Saksunarvatn Ash (Mangerud et al., 1986; Wastegard et al., 2001). The Saksunarvatn Ash has previously been described in lake sequences on Shetland (Bennett et al., 1992). The ash is dated elsewhere to ca 9000 ^{14}C yr BP (Birks et al., 1996) and 10,180±60 ice core years (Grönvold et al., 1995).

Table 3.

Microprobe analyses of 11 glass shards from the Saksunarvatn Ash, Loch of Benston

SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total
49.800	2.790	12.970	13.841	0.275	5.594	10.023	2.393	0.336	98.022
49.979	2.827	12.924	13.481	0.208	5.648	10.188	2.553	0.328	98.138
50.289	3.053	12.774	13.770	0.278	5.640	9.985	2.592	0.299	98.681
49.827	2.984	12.834	13.729	0.274	5.784	10.102	2.573	0.327	98.436
49.229	2.900	13.673	14.357	0.230	5.913	9.982	2.553	0.398	99.234
49.048	2.923	13.418	14.533	0.150	5.593	9.997	2.679	0.344	98.683
49.234	2.826	13.487	14.638	0.240	5.665	9.896	2.580	0.371	98.936
49.042	3.032	13.079	14.062	0.244	5.713	10.103	2.626	0.390	98.291
49.033	2.792	13.078	14.230	0.208	5.531	10.081	2.422	0.347	97.723
49.789	2.961	13.706	14.789	0.254	5.102	10.208	2.696	0.374	99.878
49.365	3.031	13.424	15.113	0.240	5.698	9.735	2.478	0.347	99.431
49.512	2.920	13.215	14.231	0.237	5.626	10.027	2.559	0.351	Average

0.439	0.100	0.336	0.507	0.038	0.202	0.134	0.096	0.030	Sdev

Note: Analysed on the ARL SEMQ microprobe at Department of Geoscience, University of Bergen, using beam current 10 nA and acceleration voltage 15 kV. Sample: Thin section, ash particles mounted in two component epoxy resin from Logitech, then ground and polished.

The lacustrine gyttja between the two events are also much thicker in Benston, we found up to 170 cm (Fig. 7) compared to only 70 cm in Garth Loch. The reason for this might be a higher sedimentation rate in Benston, but more likely it is due to less erosion by the younger tsunami. We searched for macrofossils for dating in the gyttja between the two tsunami units but could not find enough material for reliable age measurements. A twig from within the youngest tsunami event was dated to 5590–5760 cal yr BP (4965±55 ^{14}C yr BP) in agreement with the ^{14}C dates in Garth Loch (Table 1, Fig. 7).

5.3. Runup of the Garth tsunami

The basin at Bridge of Walls shows that the high tide level at 5500 cal yr BP was clearly lower than 2 m below present high tide. The Loch of Benston is 1.6 m above high tide. This adds up to a minimum runup of 3.6 m. However, according to the sea level curves (Fig. 4), the sea level at 5500 cal yr BP is between 7 and 12 m below present high tide. Thus, runup is probably more than 10 m for the Garth tsunami event.

6. The Dury Voe event (1500 cal yr BP)

6.1. Ayre of Dury in Dury Voe

A sand layer is seen in numerous peat outcrops from the shore and some 400 m inland at the Ayre of Dury (Fig. 2 and Fig. 8). The sand layer is 1–5 cm thick and has a sharp lower boundary. The sand is fine to medium grained and rests on ca 1 m of peat (Fig. 9). However, in a small depression inland, we cored about 2.5 m of peat and organic sediments below the sand. The sand layer was traced to 5.6 m above high tide level towards the eastern valley slope. Along the valley floor it was traced about 400 m from the present shore and levelled up to 3.3 m above high tide level. The sand layer thins inland.

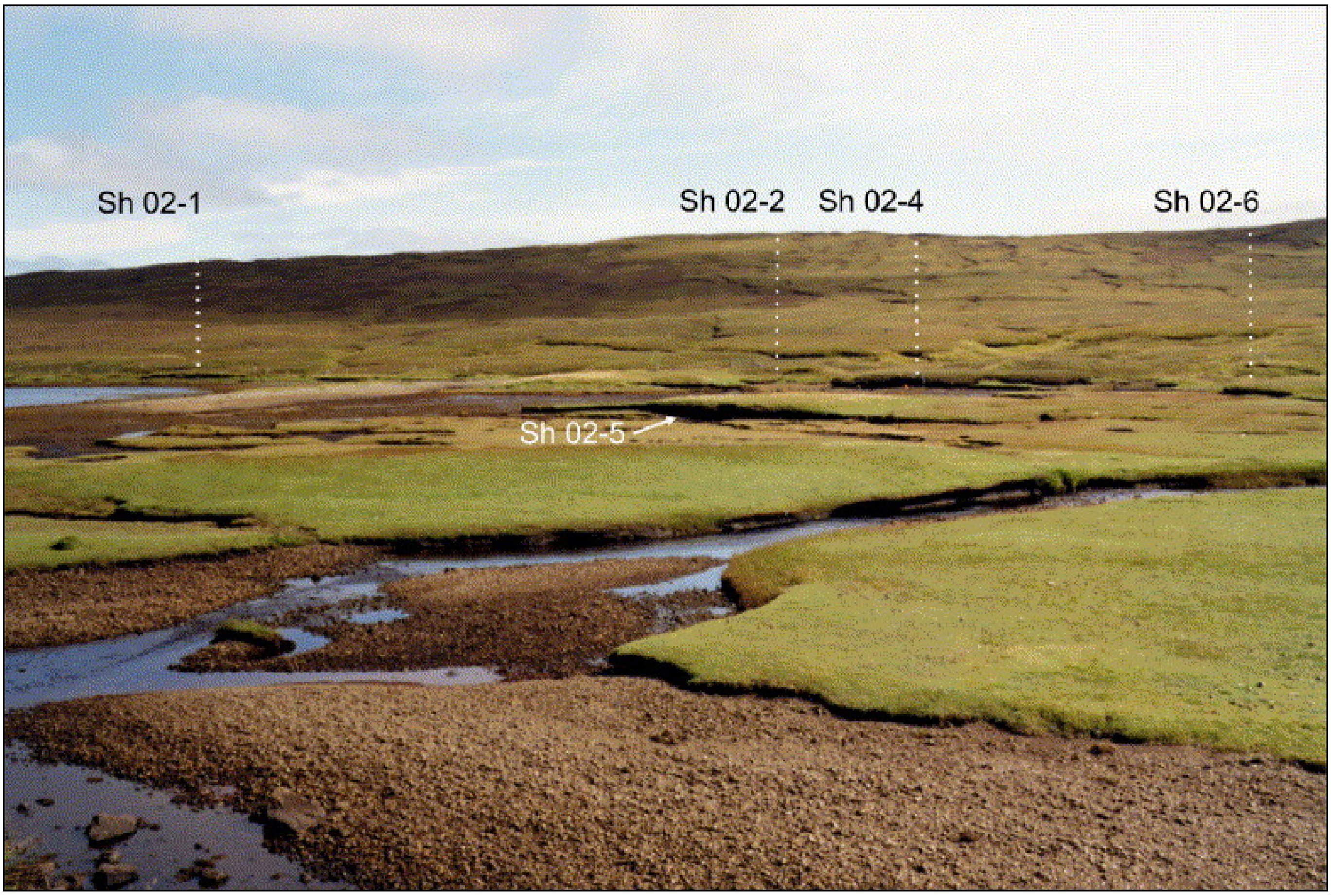


Fig. 8. The peat outcrops at the inner part of Dury Voe. The sea is barely seen at the left-hand side of the picture but inundates the channels between the peat outcrops on high tide. The distance between location Sh 02-1 and Sh 02-6 is 120 m. A sand layer was traced from one outcrop to the other and continuous inland from Sh 02-6 for more than 250 m. The sand layer was traced up to 5.5 m above high tide.

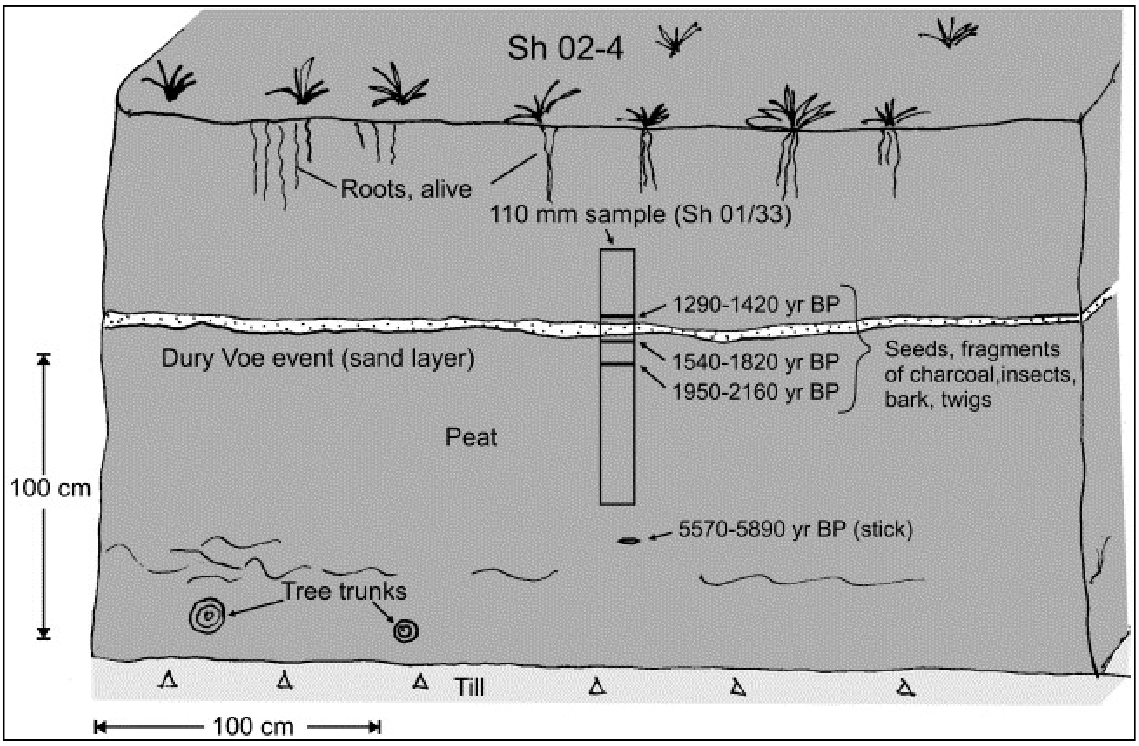


Fig. 9. A 3 m long section at site Sh 02-4 (Fig. 8) at the inner part of Dury Voe. Tree trunks are present in the lower part of the peat. The stratigraphically youngest piece of a tree was found 62 cm below the sand layer and dated to 5570–5890 yr BP (4910±90 ^{14}C yr BP). The sand layer is older than 1290–1420 yr BP (1460±50 ^{14}C yr BP) and younger than 1540–1820 yr BP (1745±60 ^{14}C yr BP). See Table 1 for further details.

There is a linear relationship between the different grain fractions of the sand and the distance from the shore. The content of medium sand (0.250 mm) and coarse sand (0.500 mm) decreases with distance from the shore (Fig. 10), and as a consequence, the finer sand fractions (0.063 and 0.125 mm) increase with distance from the shore. This demonstrates that the sand was deposited from the seaward direction and that the process depositing the sand decreased in strength, i.e. its capacity to carry larger grains inland. The larger grains, from medium sand (0.250 mm) to fine gravel (>2 mm) were deposited first, and only the finer sand grains were carried to the farthest sites away from the shore. This relationship has been documented from a number of tsunami deposits (e.g. Atwater and Moore, 1992; Minoura et al., 1996; Bondevik et al., 1997b; Dawson and Shi, 2000).

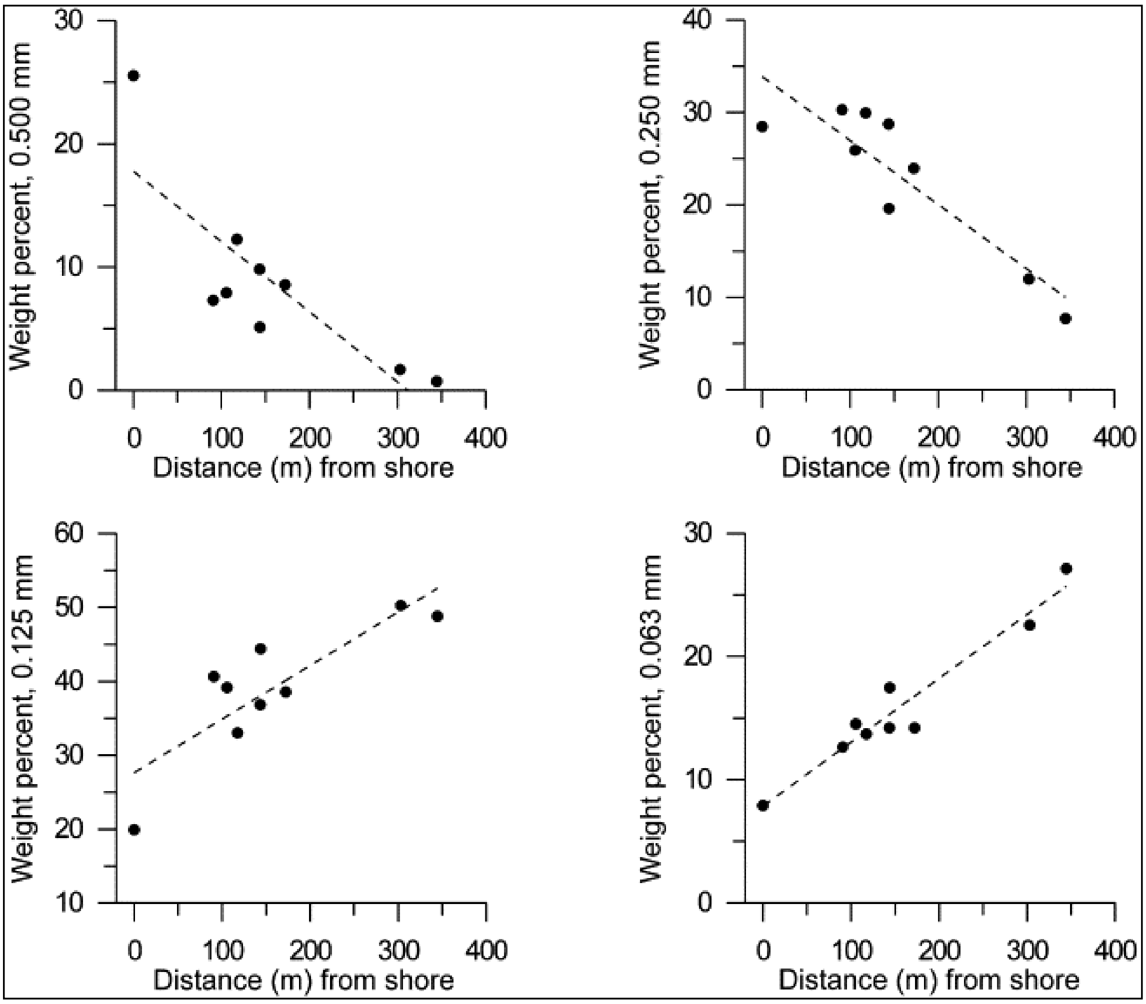


Fig. 10. Plots of grain size versus distance from the shore of the sand layer at Dury Voe (Fig. 8 and Fig. 9). The content of medium and coarse sand decreases with distance from the shore indicating that the sand was deposited from the sea. Stippled lines are best fit of a linear equation to each data set. R^2 (coefficient of determination) is between 0.68 and 0.93.

X-ray images show the sand layer to have a sharp lower boundary to the peat, although in the field we did not find proofs of erosion. We looked specifically for rip-up clasts of peat in the sand, as described for the Storegga tsunami at Maggie Kettle's Loch (see above; Bondevik et al., 2003) but did not find any. The sand is massive, without any internal structure. The upper boundary is distinct but usually not as sharp as the lower. Often there are patches or lenses of sand at the upper boundary, probably caused by vegetation and subsequent growth of the peat.

The sand layer is densely perforated with roots. Luckily we found enough material for reliable AMS ^{14}C dates; mainly seeds, charcoal and insect remains (Table 1). The dates confine the age of the sand layer to between 1540–1820 cal yr BP (1745±60 ^{14}C yr BP) and 1290–1420 cal yr BP (1460±50 ^{14}C yr BP).

6.2. Basta Voe

At the inner part of Basta Voe at the island of Yell (Fig. 2) there are three separate sand layers in peat cliffs along the shore. The two older sand layers could only be traced for a few tens of metres along the shore and were not found in sections or cores up-hill. Partly because of the short time available at the site, we were not able to determine the genesis of the two lower sand layers.

The youngest sand layer was mapped and described along the shore cliff for at least 200 m. It was also traced in peat sections up-hill, where it tapers off and ends ca 5.5 m above high tide. It varies in thickness from a few grains to 4.5 cm; along most part of the section it is 1.5 cm thick. The sand is fine grained and seems to be slightly coarser at the base. In the field, we considered the possibility that this sand was deposited from wind. However, a 10 cm cobble was found within the sand (photo in Dawson and Shi, 2000). Landwards of the cobble a tail of sand had accumulated. This indicates transport by water from the shore.

Five samples of mainly *Calluna* sp. twigs were extracted from the peat and AMS radiocarbon dated. The two dates from the upper sand bracket the age between 1330–1570 cal yr BP (1570±55 ^{14}C yr BP) and 1300–1520 cal yr BP (1505±60 ^{14}C yr BP, Table 1), similar to the age of the sand layer in Dury Voe ca 40 km to the south.

6.3. Is the 1500 yr-old sand layer in peat deposited from a tsunami?

According to the grain size analysis and the thinning of the bed inland/upslope the sand was deposited from the shore/sea side. The only possible depositing agents seem to be wind, storm surge or a tsunami. The sand layer was traced up to 5.6 m above high tide in Dury Voe and 5.5 m in Basta Voe. This is much too high to be reached by any storm surge. Storm surges generated by wind and low atmospheric pressure may give maximum surges of 1–2 m above astronomical tides (Gjevik and Røed, 1976). In a study of resent storm deposits in Canada sand was found up to the elevation of the top of the barrier beach ridge (Tuttle et al., 2004). We consider eolian activity as a more likely alternative. However, there is no accumulation of eolian sand in Dury Voe or Basta Voe today. We saw no older eolian accumulations in the area either. There is only one continuous sand layer within the peat outcrops in Dury Voe. If it was deposited from wind we would expect several layers at different levels in the peat. Also, the sand in Dury Voe has a few grains >2 mm, and, in Basta Voe, even a cobble. Such large particles are not transported by wind. All observations are compatible with an interpretation of the sand as deposited by a tsunami dated to ca 1500 cal yr BP.

7. Discussion

The tsunami deposits reported here occur on the north and east coasts of Shetland (Fig. 2). We did not discover any tsunami deposits in the western part (e.g. the basin 2 m below high tide at Bridge of Walls) or in the southern part (e.g. basin in Aiths Voe south of Lerwick located ca 1 m above high tide, Fig. 2). If a tsunami inundated these areas, runup was probably less than the subsequent sea level rise; i.e. the tsunami did not reach as high as the present day shore. This geographical distribution of the tsunami deposits could be an indication that the tsunami waves originated somewhere north and/or east of Shetland. We know this is the situation for the Storegga tsunami, triggered from the Storegga slide to the north (Fig. 1).

The Storegga slide was a huge landslide failure located rather close to Shetland (Fig. 1). It is thus tempting to consider that also the two younger tsunamis were generated from slides there. However, comprehensive marine-geological investigations in the Storegga area, due to the development of the Ormen Lange gas field (Bryn et al., 2003; Solheim et al., 2005), did not reveal any big slides that are younger than the main slide dated to 7250±250 ^{14}C yr BP (8550–7550 cal yr BP) (Haflidason et al., 2005). There has been a slide, dated to ca 5700 cal yr BP from the northern back wall of the Storegga slide. Considering the age it is a candidate for the ca 5500 cal yr tsunami on Shetland, although the slide is relatively small (Haflidason et al., 2005). The direction of the slide, however, is towards the NE part of Shetland.

The Trænadjupet slide, farther north (Fig. 1), has a minimum age of ca 4000 ^{14}C yr BP (about 4400 cal yr BP) and had a total volume of 900 km^3 (Laberg and Vorren, 2000; Laberg et al., 2002). Bondevik (unpublished) and Drange (2003) have cored a number of basins in northern Norway in search of tsunami deposits from this event, but so far have not found any. The ^{14}C dates of the slide are minimum ages and, considering its age, it might thus be possible that this slide could have triggered the 5500 cal yr BP tsunami event. At present it is unknown if the Trænadjupet slide generated a tsunami.

The most recent slides known on continental margins around the Faroe Islands (Fig. 1) happened close to 10,000 ^{14}C yr BP (van Weering et al., 1998; Kuijpers et al., 2001). This is consistent with the observations that no younger tsunami deposits were found in the lake holding Storegga tsunami deposits on the Faroe Islands (Grauert et al., 2001). The Afen slide, dated to after 5800±60 ^{14}C yr BP (Wilson et al., 2003) on the Shetland slope of the Faroe–Shetland Channel (Fig. 1) is probably too small (0.4 km^3) to generate a tsunami of any size.

We have investigated several lakes close to present day sea level in western Norway, but have so far not seen any traces of a 1500-yr-old tsunami. This might suggests that the 1500 cal yr event is a more local and/or smaller event triggered close to Shetland. However, we discovered sand layers in two lake basins located on and near Bergsøy (Fig. 1) that might correlate with the 5500 cal yr BP tsunami layers on Shetland.

The basins, called Kulturmyra (p. 41 in Bondevik et al., 1997a) and Kjerringnesvatnet, have very clear and distinct deposits from the Storegga tsunami overlain by about 4 m massive, marine silty-sandy, organic mud. However, in the middle of this latter unit there is a distinct sand layer, from 7 to 30 cm thick. It has a sharp lower boundary, contains sorted, medium sand with gravel particles (up to 3 cm longest axis), and terrestrial plant fragments (leaves). The upper boundary is gradual, and the layer is graded. The sand layer becomes thicker and coarser towards the outlet, indicating it was deposited from the sea side. If we assume constant sedimentation after the Storegga tsunami, the lower boundary of the sand is about 5500 cal yr BP in both basins—approximately the same age as in Shetland. Possibly then, the 5500 cal yr BP tsunami also inundated the coast of western Norway.

We also emphasize that the geographical distributions of the two younger tsunamis are poorly known. Part of the reason for this is that studies of tsunami deposits are limited in this area. In addition, tsunami runup is strongly influenced by bathymetry and topography, especially for smaller tsunamis. Even where tsunamis hit, the pattern of erosion and deposition is patchy. In order to find deposits from a tsunami the tsunami has to cross over a sediment source, like a sandy sea floor or sandy beach and there must be some kind of a sediment trap landwards to preserve the deposit like a lake basin, marsh or a fen. Very often those requirements are not fulfilled and a preserved tsunami deposit covers thus but a small percentage of the total area overrun by the tsunami, like the Grand Banks tsunami of 1929 (Tuttle et al., 2004) and the 1700 tsunami in the north west US (Hemphill-Haley, 1996). One should thus be very careful making conclusions about tsunamis from negative evidence. The conclusion is that the triggering mechanism is known only for the Storegga tsunami. The slides that triggered the 5500 and 1500 cal yr BP tsunamis are unknown; alternatively they could also have been triggered from other sources including earthquakes or meteorite impacts. However, we maintain that the slide from the northern back wall of the Storegga slide is a candidate for the 5500 cal yr BP.

8. Conclusions

(1) We have identified deposits from three tsunamis on Shetland. The oldest is the Storegga tsunami dated to ca 8100 cal yr BP (or ca 7300 ^{14}C yr BP), a younger event called Garth tsunami dates to ca 5500 cal yr BP (4800 yr ^{14}C yr BP) and the youngest is about 1500 years old.

(2) Deposits from the Storegga tsunami were found at several sites in the Sullom Voe area, in two lake basins in South Nesting and in two lake basins on the island of Unst. Based on empirical sea level data runup is at least 20 m in the Sullom Voe area and at least 12–15 m elsewhere on the north-eastern coast. However, runup could have been much larger because relative sea level observations from this period are limited and geophysical model predictions of past sea levels are therefore poorly constrained.

(3) In two lake basins in Garth in South Nesting, a tsunami deposit occurs in stratigraphic superposition to the Storegga tsunami deposits. The deposit dates to about 5500 cal yr BP. According to the constructed sea level curve runup for this event is probably more than 10 m. The sedimentary facies are similar to the Storegga tsunami deposits in the same lakes, and are also similar to Storegga tsunami deposits in lake basins along the Norwegian coast (Bondevik et al., 1997b).

(4) The youngest tsunami deposit is a sand layer dated to ca 1500 cal yr BP and found at two sites 40 km apart. The sand occurs as a distinct layer in thick peat, it fines and thins inland and was levelled to 5–6 m above high tide at both sites.

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